Electron kinetics inferred from observations of microwave bursts during edge localised modes in the Mega-Amp Spherical Tokamak

S.J. Freethy[1], K.G. McClements[2],S.C. Chapman[3],R.O. Dendy[2,3],
W.N. Lai[3], S.J.P. Pamela[2], V.F. Shevchenko[2],R.G.L. Vann[4]
[1] *Max Plank Institute for Plasma Physics, Boltzmann Str., Garching, Germany*
[2] *CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*
[3] *Centre for Fusion, Space and Astrophysics, Warwick University, Coventry, CV4 7AL, UK*
[4] *York Plasma Institute, University of York, York, YO10 5DQ , UKS*

The instability that initiates ELMs is relatively well understood at the fluid level of description (see e.g. [1]). However the observations reported here of electromagnetic radiation from plasmas with ELM activity indicate that the physics of this process incorporates electron kinetic effects that are not included in fluid descriptions, and occur on relatively short lengthscales and timescales. In the Mega Amp Spherical Tokamak (MAST) [2], ELMs are accompanied by intense bursts of microwave emission (BMEs) in the electron cyclotron (EC) frequency range. These can reach brightness temperatures 3-4 orders of magnitude higher than the thermal background and detailed experimental accounts of similar emission in other devices are given in [3, 4, 5, 6]. Recently, it has been shown that a plausible explantation for these bursts of emission is through the mechanism of the Anomalous Doppler Instability (ADI) [7].

An electron with velocity parallel to the magnetic field $v_\parallel$ is in resonance with a wave of frequency ω and parallel wavevector $k_\parallel$ if

$$\omega = \ell\Omega_e + k_\parallel v_\parallel, \tag{1}$$

where ℓ is an integer and Ω_e is the EC frequency. The ADI occurs when waves are excited via this resonance condition with $\ell < 0$; in applications of the ADI to tokamak plasmas, the case $\ell = -1$ is generally found to be relevant [8]. As the ADI proceeds, the suprathermal electrons acquire perpendicular momentum comparable to their parallel momentum on timescales of a few hundred EC periods, τ_c. While predominantly electrostatic, the waves can be converted to electromagnetic waves, and thus propagate freely to antennas outside the plasma [9].

BME intensities relative to the average thermal background level peak at about 35dB and extend up to 40 dB. Measurements show the peak of the microwave burst activity occurs around 20μs before the peak in midplane deuterium-α (D_α) line emission. In many cases a burst of X-ray emission coincides with the microwave burst, with the peak emission again preceding the D_α emission by around 20μs in the crash phase [10].

Simulations of ELMs in MAST performed with the nonlinear resistive MHD code JOREK [11] reveal that parallel electric fields of up to 2kVm^{-1} can be expected in localised regions (Fig. 1). Mirnov coil measurements during ELMs in MAST imply that the modes associated with these fields have periods of the order of a few microseconds; individual electrons would be accelerated to tens of keV if they encountered 2kVm^{-1} parallel electric fields for only a small fraction of this time.

To investigate the stability of field-aligned superthermal electrons, particle-in-cell (PIC) simulations have been carried out in one space dimension and three velocity dimensions, the magnetic field being tilted at an angle of 45° with respect to the space axis. Thus, any excited waves have wavevectors with components parallel ($k_{\parallel}$) and perpendicular ($k_{\perp}$) to **B** of equal magnitude, i.e. $k_{\parallel} = k_{\perp}$. The location in the MAST plasma of the instability producing the microwave bursts is not known precisely. PIC simulations have been carried out with a range of values of initial bulk electron density n_e, from $2 \times 10^{18}\text{m}^{-3}$ to $4 \times 10^{19}\text{m}^{-3}$, covering the MAST edge conditions. In all cases the initial electron distribution comprises a Maxwellian bulk with a temperature T_e of either 100eV or 20eV and a flat magnetic field-aligned tail, containing 5% or 10% of the total electron population and extending to 20 or 40 times v_B where $v_B = (2T_e/m_e)^{1/2}$ is the initial bulk electron thermal speed, m_e being the electron mass. It is known that the growth-rate of the ADI is linearly dependant on the fractional density of fast electrons n_f/n_e, so we may extrapolate the measured growth rates to smaller fractional densities if necessary. In all cases the equilibrium magnetic field B_0 is 0.4T, a typical value in the outer midplane edge of MAST plasmas. Analysis of the PIC data reveals propagating waves close the the upper-hybrid-frequency [7]. These waves may convert to electromagnetic waves in this region and be detected by antennas outside the plasma.

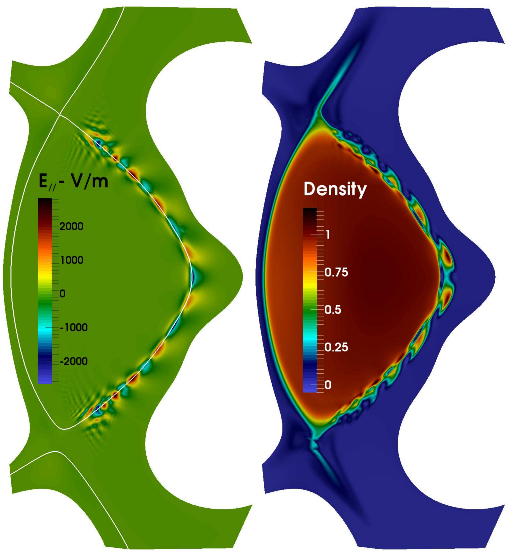

Figure 1: Poloidal snapshots of parallel electric field (left plot) and plasma density normalised to the magnetic axis value (right plot) in a JOREK simulation of an ELM in MAST [11]. The white curve in the left plot shows the separatrix.

Fig. 2 shows (a) the initial electron velocity distribution in this simulation and (b) the distribution after $379.4\tau_c \simeq 30\text{ns}$. It is apparent that, in this short time, the electrons in the tail acquire perpendicular momenta comparable to their initial parallel momenta. We conclude that strongly field-aligned energetic electron distributions in the edge plasma of MAST are very rapidly isotropised via the ADI. We note that the forward-propagating waves in the upper hybrid frequency range have wavevectors $k \sim 0.1\omega_{pe}/v_B$ and hence $k_{\parallel} \sim 0.1\omega_{pe}/(\sqrt{2}v_B)$. Using this value of $k_{\parallel}$ in Eq. (1) and setting $\omega = 1.2\omega_{pe}$, $\ell = -1$ we find that the anomalous Doppler resonance condition is satisfied by electrons with $v_{\parallel} \sim 30v_B$; we note from Fig. 2 that this is close to the parallel velocity at which electrons have acquired the largest boost in $v_{\perp}$, and conclude from this that the ADI explains the excitation of the high amplitude waves observed in this simulation.

Similar phenomena are observed in PIC simulations with higher n_e ($\geq 10^{19}\text{m}^{-3}$) and T_e (100eV), more characteristic of the top of the H-mode pedestal region in MAST plasmas. However, as in the low density case discussed above, high amplitude waves are only excited in these simulations at frequencies either below Ω_e or above ω_{pe}. Neither of these frequency ranges is compatible with the observed frequency peak, if $B_0 = 0.4$ and $n_e \geq 10^{19}\text{m}^{-3}$. Only in the low density simulation do we see wave excitation at frequencies that are consistent with the BME spectra, suggesting that the energetic electrons causing the emission undergo acceleration very close to the MAST plasma edge. This conclusion is bolstered by the predictions from JOREK shown in Fig. 1. A corollary of this last conclusion is that the energetic electrons are likely to have a very short confinement time, particularly in view of the fact that the magnetic field in the plasma edge region is strongly distorted by the ELM instability. In these circumstances we expect the electrons to be subject to rapid cross-field transport of the type discussed by Rechester and Rosenbluth [12], an idea explored more quantitatively in [7]. Analysis of the soft X-ray data reveals that a rather modest fraction of super thermal electrons is required to produce the observed rise, of the order of 10^{-3} or less.

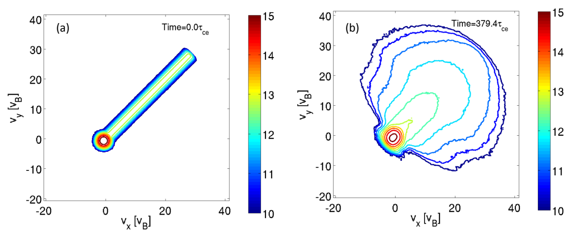

Figure 2: Contours of (a) initial and (b) final electron velocity distribution in PIC simulation with initial electron density $2 \times 10^{18}\text{m}^{-3}$ and nonthermal electron tail fraction of 5%. The colour bar has a logarithmic scale.

In conclusion, measurements of microwave and soft X-ray emission during ELMs in spherical tokamak plasmas provide strong evidence for the transient presence in the edge plasma of highly suprathermal electrons. The paradoxical nature of the intensity of the emission, given the absence of any RF wave heating is resolved by considering the response of electrons accelerated by a parallel electric field and invoking the collective anomalous Doppler instability. Particle-in-cell simulations show that magnetic field-aligned energetic electron distributions, of the kind inferred to result from parallel electric fields generated by ELMs, excite electromagnetic waves in the electron cyclotron range. Further, the PIC simulations predict emission frequencies between ω_{pe} and ω_{UH}, which is consistent with the predictions from JOREK regarding the radial location of the accelerating field. While soft X-ray and Thomson scattering data indicate that the fraction of accelerated electrons is small, their active role suggests that purely fluid models of ELMs are incomplete. For example the radial current associated with the rapid radial transport of these electrons could have an effect on ELM dynamics, and, if sufficiently energetic and present in sufficiently large numbers, they could cause damage to plasma-facing components. For these reasons it is hoped that the present study will prompt further investigations of energetic electron production during ELMs.

This project has received funding from the RCUK Energy Programme (grant number EP/I501045) and from Euratom. Assistance from Luca Garzotti and Rory Scannell on the interpretation of soft X-ray and Thomson scattering data is gratefully acknowledged. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] G.T.A. Huysmans *et al.*, Plasma Phys. Controlled Fusion **51**, 124012 (2009).
[2] B. Lloyd *et al.*, Nucl. Fusion **51**, 094013 (2011).
[3] C.H. Fuchs, M.E. Austin, Phys. Plasmas **8**, 5 (2001).
[4] G. Taylor *et al.*, Nucl. Fusion **32**, 1867 (1992).
[5] M.E. Austin *et al.*, *Proc. 14th Joint Workshop on ECE and ECRH*, *Santorini* (2006).
[6] D.V. Bartlett *et al.*, *Proc. 8th Joint Workshop on ECE and ECRH*, *Gut Ising* (1993).
[7] S.J. Freethy *et al.*, Phys. Rev. Let. **114**, 125004 (2015).
[8] W.N. Lai, S.C. Chapman, and R.O. Dendy, Phys. Plasmas **20**, 102122 (2013).
[9] A.K. Ram, A. Bers, and C.N. Lashmore-Davies, Phys. Plasmas **9**, 409 (2002).
[10] A. Kirk *et al*, Phys. Rev. Lett., **96**, 185001 (2006)
[11] S.J.P. Pamela *et al*, Plasma Phys. Control. Fusion **55**, 095001 (2013)
[12] A.B. Rechester, M.N. Rosenbluth, Phys. Rev. Lett. **40**, 38 (1978).
[13] H.A. Kramers, Phil. Mag. Series 6 **46**, 836 (1923).